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HEAVY NEUTRINO MASSES AND MIXINGS AT THE LHC*

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The $pp \to lljj$ process is analysed assuming right-handed currents and heavy Majorana neutrinos. We discuss dependence of the cross section $\sigma(pp \to lljj)$ on the ratio $g_{\rm R}/g_{\rm L}$ of right and left gauge couplings. Estimation of the signal strength is given for $\sqrt{s} = 8$ TeV and 14 TeV with $g_{\rm R}/g_{\rm L} = 0.6$ and $g_{\rm R}/g_{\rm L} = 1$.

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1. Introduction

Recently, several excesses in the invariant mass distributions were reported by the ATLAS and CMS experiments at the $\sqrt{s} = 8$ TeV in $pp \to jj$ [1–5] and $pp \to lljj$ [6–8]. Curiously, for all channels, the excesses occurs around similar value of the invariant mass: 1.8–2.2 TeV. Although these data are not statistically significant yet and await verification in the Run 2 of the LHC, they already drew a lot of attention.

One of the attempts to interpret these experimental data within a single framework is to assume a presence of right-handed currents. In such a scenario, an additional heavy gauge boson $W_2^{\pm}$ is produced in the pp collision. It further decays either to two quarks leading to the dijet signal, or to WZ/Wh^0 leading to diboson signal [9–13] or to a charged lepton l and a heavy neutrino N_a [14]. The latter, in turn, decays mainly to a charged lepton and two jets jj. The whole process $pp \to W_2 \to N_a l \to lljj$ is especially interesting because events with the same-sign (SS) leptons in the final state would clearly signal lepton number violation [15–24].

In this paper, we extend slightly our previous analysis of $pp \to W_2 \to N_a l \to lljj$ given in [21] presenting analytical formulae for both neutral and charged gauge boson masses and their mixings matrices for $g_{\rm L} \neq g_{\rm R}$. They

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will be used and explored in detail in the forthcoming analysis [25]. We also provide estimations of the cross section $\sigma(pp \to eejj)$ for $\sqrt{s} = 14$ TeV and $g_{\rm R} = g_{\rm L}$ and $g_{\rm R} = 0.6 g_{\rm L}$, not discussed in [21]. Since publishing [21], the process $pp \to eejj$ has been discussed *e.g.* in [9, 12, 13, 22, 26–32].

2. The LHC and $pp \to eejj$ in the MLRSM

We focus on the Manifest Left–Right Symmetric Model (MLRSM) based on the $\mathrm{SU(2)_L} \times \mathrm{SU(2)_R}$ gauge symmetry [33, 34]. Details of the model and more comprehensive list of references can be found *e.g.* in [35, 36]. The model under consideration contains three heavy neutrinos N_a, $a = 1, 2, 3$. We assume that their masses are of the order of 1 TeV and they couple to the charged heavy gauge boson $W_2^\pm$ in the following way:

$$\mathcal{L} \;\supset\; b \frac{g_{\rm L}}{\sqrt{2}} \overline{N}_a \gamma^\mu P_{\rm R} (K_{\rm R})_{aj} l_j W_{2\mu}^+ + \text{h.c.}\,, \tag{1}$$

where $b = g_{\rm R}/g_{\rm L}$ is the ratio of the right and left gauge couplings. A direct inspection of matrix elements related to the process $pp \to lljj$ shows that beside $\sqrt{s}$, there are basically three variables that rule the magnitude of the cross section: b, mixing matrix $K_{\rm R}$ and mass ratios $x_a = M_{N_a}^2 / M_{W_2}^2$ [21]. As the CMS did not find any excess in the $pp \to \mu\mu jj$ channel [7], the first guess is that N_e practically does not couple to μ and N_μ is much heavier than W_2. Such scenario can be described by setting $M_{N_{1,3}} = 0.925$ TeV, $M_{N_2} = 10$ TeV and choosing the following form of $K_{\rm R}$:

$$K_{\rm R} = \begin{pmatrix} \cos\theta_{13} & 0 & \sin\theta_{13} \\ 0 & 1 & 0 \\ -e^{i\phi_3}\sin\theta_{13} & 0 & e^{i\phi_3}\cos\theta_{13} \end{pmatrix}. \tag{2}$$

Such a form of $K_{\rm R}$ seems to be in a good agreement with the data reported by the CMS and ATLAS. The dependence of the cross section for the reaction $pp \to eejj$ in the scenario defined by (2) is shown in Fig. 1. Moreover, due to $K_{\rm R12} = K_{\rm R21} = 0$, contributions to $\mu \to e\gamma$ are negligible in this case.

Let us stress that interferences between degenerate heavy neutrinos have to be carefully treated as they may lead to decreasing of the same-sign signatures in the final state, see Fig. 1. It turns out that the influence of heavy neutrinos N_a, their interferences and mixings, can be conveniently described with the help of two following quantities [21]:

$$r \;=\; \frac{\sigma_{e^+e^+} + \sigma_{e^-e^-}}{\sigma_{e^+e^-}}\,, \tag{3}$$

$$\gamma \;=\; \frac{\sigma_{e^+e^+} + \sigma_{e^-e^-} + \sigma_{e^+e^-}}{(\sigma_{e^+e^+} + \sigma_{e^-e^-} + \sigma_{e^+e^-})|_{b=1,\theta_{13},\phi_3=0}}\,. \tag{4}$$

One can check that γ depends on b and scales as $\gamma \sim b^2$. On the other hand, r does not depend on the value of b because both numerator and denominator in the definition of r in (3) scales as b^2.

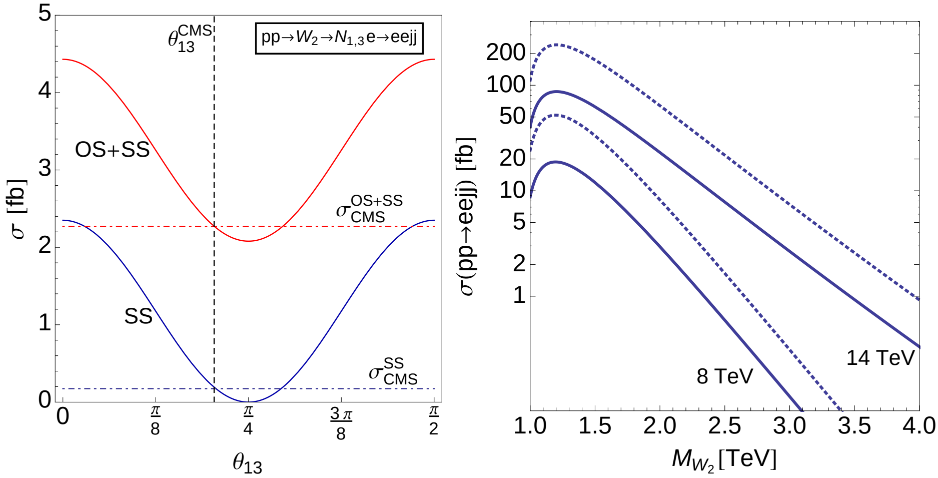

Fig. 1. Left panel: Cross section for the production of two leptons ee and two jets jj *vs.* mixing angle θ_{13} calculated within MLRSM model with $b = 1$. The same-sign (SS) and cumulative *i.e.* opposite-sign + same-sign (OS+SS) contributions to the cross section are shown. Horizontal dot-dashed lines represent values of cross sections measured by the CMS. Dashed vertical line corresponds to the value of $\theta_{13}^{\mathrm{CMS}} = 0.64$ for which the cross section has the same value as measured by the CMS. Right panel: Cross section for the process $pp \to eejj$ *vs.* mass of charged gauge boson M_{W_2} for $\sqrt{s} = 8, 14$ TeV and $b = 0.6$ (solid lines) and $b = 1$ (dashed lines). Lower dashed line corresponds to $\sqrt{s} = 8$ TeV and $b = 1$, while upper dashed line corresponds to $\sqrt{s} = 14$ TeV and $b = 1$.

It turns out that one can find such values of θ_{13} and ϕ_3 that $r = 1/13$ and $\gamma = 0.54$ what reproduces excess in the data related to $pp \to eejj$ reported by the CMS. For example for $\phi_3 = \pi/2$, the value of the angle θ_{13} has to be $\theta_{13}^{\mathrm{CMS}} = 0.64$.

To show the role played by the ratio b, we display in Fig. 1 results of numerical simulation in the MadGraph5 (v2.2.2) [37] for $\sqrt{s} = 8, 14$ TeV and two values of b: 0.6 and 1. In the left panel of this figure, one can see that the cross section does depend on the value of b. Approximately, it is 2.8 times bigger for $b = 1$ than for $b = 0.6$. To generate an UFO file [38], we have used our implementation of the MLRSM in the FeynRules (v2.0.31) [39].

In summary, we have shortly discussed how the ratio $g_{\rm R}/g_{\rm L}$ and heavy neutrinos mixing matrix $K_{\rm R}$ influence cross section for the process $pp \to lljj$. Hopefully, Run 2 of the LHC will provide enough data to allow to verify the excesses in $pp \to jj$ and $pp \to eejj$ reported by the ATLAS and CMS. This would be crucial information for the Beyond Standard Model scenarios involving additional heavy gauge bosons.

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Appendix

Here, we present explicit analytical formulae for masses of the charged and neutral gauge bosons, $M^2_{W_{1,2}}$ and $M^2_{Z_{1,2}}$ respectively, and orthogonal matrices U_W, U_Z which relate gauge eigenstates and mass eigenstates in the Manifest Left–Right Symmetric Model with arbitrary $b = g_{\rm R}/g_{\rm L}$. For simplicity, we assume that the mass matrices of both charged and neutral gauge bosons, $\widetilde{M}^2_W$ and $\widetilde{M}^2_Z$ respectively, are real. A Mathematica file gLgR with these formulae altogether with their tests can be downloaded from `http://www.tjel.us.edu.pl/tools.html`

The mass matrix of the charged gauge bosons is of the following form

$$\widetilde{M}^2_W = \frac{1}{4} g^2_{\rm L} v^2_{\rm R} \begin{pmatrix} c_+ & -2c_{12}b \\ -2c_{12}b & (2+c_+)b^2 \end{pmatrix}, \tag{5}$$

where $c_+ = (\kappa_1^2 + \kappa_2^2)/v^2_{\rm R}$ and $c_{12} = \kappa_1\kappa_2/v^2_{\rm R}$. The corresponding masses of charged gauge bosons are

$$M^2_{W_{1,2}} = \frac{g^2_{\rm L} v^2_{\rm R}}{8} \left\{ c_+ + 2b^2 + c_+ b^2 \mp \sqrt{16 c^2_{12} b^2 + \left[c_+ - (2+c_+)b^2\right]^2} \right\}. \tag{6}$$

The gauge eigenstates $\boldsymbol{W}_g = (W^\pm_{\rm L}, W^\pm_{\rm R})^T$ and mass eigenstates $\boldsymbol{W}_m = (W^\pm_1, W^\pm_2)^T$ are related by the orthogonal transformation $\boldsymbol{W}_g = U_W \boldsymbol{W}_m$, where

$$U_W = \begin{pmatrix} \cos\xi & \sin\xi \\ -\sin\xi & \cos\xi \end{pmatrix}. \tag{7}$$

The mixing angle ξ in (7) is given by the following relation:

$$\tan 2\xi = -\frac{4bc_{12}}{2b^2 - (1-b^2)c_+}\,. \tag{8}$$

The mass matrix of the neutral gauge bosons is of the following form

$$\widetilde{M}_Z^2 = \frac{1}{2} g_{\rm L}^2 v_{\rm R}^2 \left(\begin{array}{ccc} \frac{c_+}{2} & -\frac{c_+ b}{2} & 0 \\ -\frac{c_+ b}{2} & \frac{1}{2}(4+c_+)b^2 & -2bb' \\ 0 & -2bb' & 2b'^2 \end{array} \right) , \tag{9}$$

where $b' = g'/g_{\rm L}$. The corresponding masses of neutral gauge bosons are

$$M_{Z_{1,2}}^2 = \frac{g_{\rm L}^2 v_{\rm R}^2}{2} \left\{ b^2 + \frac{1}{4} c_+ \left(1+b^2\right) + b'^2 \mp \sqrt{\frac{1}{16}\left[c_+(1+b^2)+4(b^2+b'^2)\right]^2 - c_+\left[b'^2+b^2(1+b'^2)\right]} \right\} . \tag{10}$$

The gauge eigenstates $\boldsymbol{Z}_g = (W_{\rm L}^3, W_{\rm R}^3, B)^T$ are related to the mass eigenstates $\boldsymbol{Z}_m = (Z_1, Z_2, A)^T$ by the orthogonal transformation $\boldsymbol{Z}_g = U_Z \boldsymbol{Z}_m$. The mixing matrix has the following form:

$$U_Z = \left(\begin{array}{ccc} c_W c_\phi & c_W s_\phi & s_W \\ -s_W s_M c_\phi - c_M s_\phi & -s_W s_M s_\phi + c_M c_\phi & c_W s_M \\ -s_W c_M c_\phi + s_M s_\phi & -s_W c_M s_\phi - s_M c_\phi & c_W c_M \end{array} \right) , \tag{11}$$

where $s_\phi = \sin\phi$, $c_\phi = \cos\phi$, $s_W = \sin\theta_W$, $c_W = \cos\theta_W$, $s_M = \tan\theta_W/b$, $c_M = \sqrt{1-s_M^2}$, $g_{\rm L} = e/\sin\theta_W$ and $g' = e/\sqrt{\cos 2\theta_W}$. The mixing angle ϕ is defined by the following relation:

$$\sin 2\phi = -\frac{c_+ g_{\rm L}^2 v_{\rm R}^2 b^2 \sqrt{b'^2 + b^2\left(1+b'^2\right)}}{2\left(b^2+b'^2\right)\left(M_{Z_2}^2 - M_{Z_1}^2\right)} . \tag{12}$$

Finally, let us note that in the limit $b \to 1$, formulae (5)–(12) reduce to (35)–(41) from paper [36].

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